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THE MUTUAL APPROACH ~~RAPPROCHEMENT~~ OF AEROSOL PARTICLES IN A SOUND FIELD

UNDER THE ACTION OF OSEEN'S HYDRODYNAMIC FORCES

[This is a translation of an article written by S. V. Pshenay-Severin in Doklady Akademii Nauk SSSR (Reports of the Academy of Sciences USSR), Vol 125, No 4, 1959, pages 775-778.]

In the studies of the mechanism of the acoustic coagulation of aerosols, hydrodynamic forces are usually regarded as one of the main causes of the mutual approach of aerosol particles in a sound field. The effect of hydrodynamic forces depends on the velocity of the flow of the air medium around the particles, V. If this velocity of medium varies according to the law $U = U_0 \sin \omega t$ ($\omega = 2\pi f$, where f is the frequency of sound), then the velocity of the steady-state motion of the individual particle equals $v = U_0 n \sin(\omega t - \varphi)$ and the ambient-flow velocity $V = U - v$ will be

$$V = U_0 n \cos(\omega t - \varphi). \tag{1}$$

где $m = \sin\varphi = \frac{\Omega}{(1+\Omega^2)^{1/2}}$; $n = \cos\varphi = \frac{1}{(1+\Omega^2)^{1/2}}$; $\Omega = \omega\tau$; $\tau = \frac{2}{9}\frac{\delta}{\eta}R^2$ —

where $m = \sin\varphi = \frac{\Omega}{(1+\Omega^2)^{1/2}}$; $n = \cos\varphi = \frac{1}{(1+\Omega^2)^{1/2}}$; $\Omega = \omega\tau$; $\tau = \frac{2}{9}\frac{\delta}{\eta}R^2$ is the relaxation time; and R is the particle radius (δ is density of particle matter, η is viscosity coefficient of the medium).

Hydrodynamic forces were investigated by Kirchhoff (Bibl. 1), Koenig (Bibl. 2), and Bjerknes (Bibl. 3) for the conditions of the flow of an ideal fluid around two spherical particles. If $\psi_{12} = \pi/2$ (Fig. 1) then each of the two identical particles is acted upon by the force of attraction $F \sim \rho R^6 V^2 / r_{12}^4$, where ρ is density of medium. The question of the necessity of taking under consideration the effect of hydrodynamic forces on the process of acoustic coagulation was posed by Andrade (Bibl. 4). In the cases of interest to practice, the concentration of aerosols usually is relatively small and, consequently, the mean distance between particles $\bar{r}_{12}$ is large. Inasmuch as the forces in

question decrease rapidly with increasing distances (as $1/r_{12}^4$), therefore it is not possible to [redacted] explain satisfactorily by the action of these forces the process of the acoustic coagulation of aerosols (Bibl. 5) and, in particular, of natural fogs (Bibl. 6), for which R~3 -- 15 microns. Thus [redacted], the question of the role of hydrodynamic interaction in this process is not to be presumed as definitely clarified, on the basis of the following considerations. The above-named [redacted] works were concerned solely with inertia forces in the ideal fluid, whereas, in the case of small aerosol particles, the corresponding Reynolds numbers are low ($Re \sim 1 - 10$). Therefore, in addition to the inertia forces acting on the element of the medium it is also necessary to consider the viscosity forces.

Viscosity forces, together with inertia forces, can be computed on the basis of Oseen's hydrodynamic equation. When an indidividual spherical particle moves in an inert [redacted] viscous [redacted] fluid and in the case of an Oseenian mode of (circumambient) [redacted] flow at considerable distances r from the center of the sphericle, the streamlines in front of the sphericle and within a narrow area in the rear of the sphericle will be radial in nature and oriented in the same direction as the sphericle (cf. Bibl. 7, page 250). In this [redacted] connection, the magnitude of the speed of movement of the medium in rear of the sphericle decreases as [redacted] 1/r, and in front of the sphericle -- as $1/r^2$. In the event [redacted] two particles are situated comparatively close to each other, [redacted] they will mutually perturb the ambient-flow fields of each other [redacted]. If the line of centers [redacted] coincides with the direction of the ambient air flow (or diverges little from that direction), then, as a result of the interaction between the two particles, the resistance of each particle should diminish; however [redacted], as a consequence of the difference in the magnitude of the speed of movement of the medium in front and in rear of each particle [redacted], the diminution in resistance will be more considerable for the "head" particle than for the "tail" one. This difference in diminution of resistance is equivalent [redacted] to the effect of a force of atraction between the two

particles. The first to examine the hydrodynamic forces of this type was Oseen (Bibl. 8, 9).

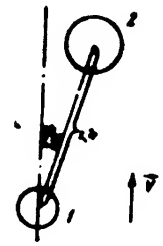

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Fig. 1. Schematic Representation of the Positions of Interacting Particles. ψ_{12} -- angle between direction of ambient flow and the line of centers of the particles; r_{12} -- distance between centers of the particles.

Inasmuch as Oseen's hydrodynamic equation is a linear one, therefr when examining the interaction between the particles, it is possible to proceed from the assumption of the superposition of the fields of the flow around the particles and ~~XXXXXXXX~~ to estimate the magnitude of the resistance force acting on each particle, according to the formula

$$D_i^* = 6\pi\eta_i R_i (V_i - u_k) S(\mathrm{Re}_i),$$

where $V_i = U - v_i$ is unperturbed ambient-flow [redacted] velocity, u_k is perturbance of the [redacted]velocity of the flow around the i-th particle, calculated according to the field of the flow around the k-th particle at the locus of the center of the i-th particle ($i = 1, 2$; $k = 2, 1$). In the given case the correction factor S is assumed equal to unity. If the particle with the subscript 1 is the "head" particle then, as a first approximation, when $R_1 = R_2 = R, \psi_{12} = 0$ and $\varepsilon = R/r_{12} \ll 1$ the following expressions can be adopted for u_1 and u_2

$$u_1 = \frac{3}{2}\varepsilon V_1, \quad u_2 = \frac{3\varepsilon^2}{\mathrm{Re}} V_2. \quad (2)$$

In the event $\varepsilon \ll 1$, the magnitude of u_2 is negligibly small compared with u_1, and it can be assumed that $u_2 = 0$; here we arrive at the scheme of the unilateral hydrodynamic effect of the "head" particle on the "tail" particle, at which the computation of the relative movement of particles in a sound field is considerably simplified. The difference in resistance forces $\Delta = D_1 - D_2$ is determined by perturbance u_1, the magnitude of which decreases with

increasing distance in inverse proportion only to the first power of r_{12} and not to the fourth power, as the magnitude of forces at potential ambient flow. Therefore, it can be expected that the effect of the interaction between particles on their relative movement will also be much greater at the Oseenian mode of ambient flow around them than at the potential one.

The afore-cited formulas are applicable, rigorously speaking, only at a stationary flow of the medium around the particles. In a sound field the velocity of the flow around particles varies in magnitude and in direction. However, if the frequency of sound is not high, it is apparently admissible to adopt the postulate of the quasistationarity of the processes occurring during the flow of air around particles with a radius of $\sim 1 - 10$ microns(Bibl. 10). Inasmuch as at an Oseenian mode of ambient flow, the resistance force is always greater for the first particle than for the second, therefore in a sound field the [redacted] mutual ~~r[redacted]ment between~~ approach of particles should occur both when the ambient flow proceeds in one direction and when it is reversed. However, it is important to consider that the difference in the magnitude of the velocity of the medium in the front and in the rear of the sphericle and hence also the difference in the magnitude of resistance forces for the "head" and "tail" particles arises only at sufficiently high Re; this difference disappears when $Re \rightarrow 0$. Therefore, let us assume that in the sound field $\Delta \neq 0$ only at those values of the [redacted] ambient-flow velocity (1) at which [redacted] the corresponding Re is greater than a certain [redacted] critical Re_{kp} (e. g., $Re_{kp} = 1$). Let t_1 and t_2 be the time instants [redacted] bounding the interval within which $|V| \geq V_{kp}$. [V critical] Let us calculate, in the case of $\psi_{12} = 0$, the elementary mutual displacement s_{12} of the identical particles relative to each other during the time interval (t_1, t_2). The magnitude of s_{12} will characterize the result of the interaction between the particles during a half-period of sound vibrations T/2. Let us assume that prior to time instant t_1 the velocity of flow around both particles changes according to law (1), while when $t_1 \leq t \leq t_2$ the velocity of flow V_1 around the particle with the subscript 1 (which is the "head" particle)

continues to vary according to formula (1) but the velocity of flow around the second ("tail") particle is expressed in the form of $\tilde{v}_2 = [(U - v_2) - \frac{3}{2}\varepsilon v_1]$. The equations of motion of the particles have the form of $\tau\frac{dv_1}{dt} = V_1, \tau\frac{dv_2}{dt} = \tilde{V}_2$. We consider the parameter ε to be constant during the time $\sim T/2$.

Let us introduce into consideration the magnitude $v_{12} = v_1 - v_2$ and let us pass over to the dimensionless variables $\theta = t/\tau$ and $\xi_{12} = v_{12}/U_0$; then ξ_{12} is determined from the equation $\frac{d\xi_{12}}{d\theta} + \xi_{12} = 1.5\varepsilon m\cos(\Omega\theta - \varphi)$ on taking into account the initial condition $\xi_{12}(\theta_1) = 0$. Inasmuch $\frac{d}{d\theta}\left(\frac{s_{12}}{U_0\tau}\right) = \xi_{12}$, therefore the integration of the expression for ξ_{12} under the condition that $s_{12}(\theta_1) = 0$, makes it possible to obtain the displacement s_{12} during the time interval (t_1, t_2) in the form

$$\frac{s_{12}}{X_0} = -1.5\varepsilon mn\{[2mn\cos\Omega\theta_2 - (n^2 - m^2)\sin\Omega\theta_2] - \frac{m}{n}[2mn\sin\Omega\theta_1 + (n^2 - m^2)\cos\Omega\theta_1]e^{-(\theta_2-\theta_1)} + (\sin\Omega\theta_1 - \frac{m}{n}\cos\Omega\theta_1)\}, \quad (3)$$

where $X_0 = U_0/\omega$.

Fig. 2 shows the results of the calculations of s_{12} for water droplets with various radii, on the basis of (3). The parameter ε was assumed constant and equal to $1 \cdot 10^{-2}$; this signifies that the droplets under study were always spaced apart from each other by a distance of [redacted] $r_{12} = 100$ R, equal [redacted] approximately to $\bar{r}_{12}$ when the concentration by weight of the droplets is one gram per cubic meter. The displacements s_{12} are related to the radius of particles R. To obtain [redacted] mutually comparable values at various sound frequencies $f = \nu \cdot 10^2$ cycles per [redacted] second (ν is an integer), the values of s_{12}/R are multiplied by the corresponding numbers ν. The curves presented in Fig. 2 are distinguished by the presence of a maximum and also by their compression along the axis of the values of R and by the displacement of the maximum to the side of lower Rs with increasing sound frequency (with increasing ν). At a given sound intensity (at a given magnitude of U_0) the magnitude of the maximum increases with increasing f only up to a limit, whereupon it begins to decrease. For a given R there exists an optimal value of sound frequency at which the maximal velocity of mutual approach [redacted] of the droplets is present. Oseen's forces are effective for the droplets in the size

range of 1.5 to 15 microns. When $R\sim 5$-15 microns, the most xx favorable sound frequencies are those of order several hundred cycles, and when $R < 5$ microns, -- of order several kilocycles.

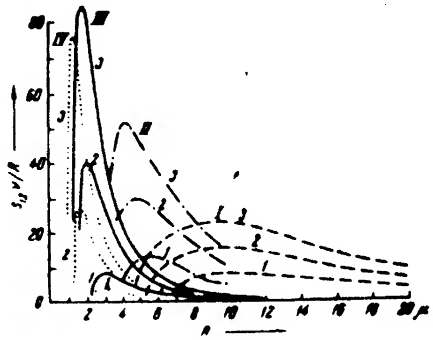

Fig. 2. Mutual R~~approchement Between~~ Approach of Droplets of Various Radius According to Sound Frequency $f = \nu \cdot 10^2$ seconds^{-1} and Sound Intensity (Velocity Amplitude U_o). The curve group I corresponds to $\nu = 1$; II -- $\nu = 5$; III -- $\nu = 50$; IV -- $\nu = 150$. Curves 1 are computed for $U_o = 400$ cm/sec; 2 -- for $U_o = 700$ cm/sec; and 3 -- for $U_o = 1{,}000$ cm/sec.

The computed time s12 of the mutual approach [redacted]t of two particles from a distance equal to the mean distance between the particles to the zero (contact) ~~distance at which~~ they are in contact constitutes the characteristic time of the coagulation process, which can be compared with the experimentally observed time t_o of the 50-percent decrease in the count of particles (Bibl. 6). The observed time t_o for natural fogs is of [redacted] order [redacted] several minutes (Bibl. 6). If however we proceed from the values of $s_{12}\nu/R$ cited in Fig. 2, then the time t_{12} will prove to be much shorter than one [redacted] second within a sufficiently broad range of sizes for each of the considered frequency values.*

Thus, Oseen's hydrodynamic forces apparently are an important factor in the enlargement of droplets with radius of 1.5 to 15 microns in a sound field of a relatively low frequency, in addition to the process of

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*Inasmuch as the values of s_{12} are calculated on the basis of approximate formulas which are not applicable for small distances, therefore, strictly speaking, these data can be used to judge about the rapprochement between particles from large distances $r_{12}\sim 100$ R to distances s_{12} 10 R but not to zero (contact) distance.

orthokinetic coagulation. The afore-cited estimates are to be regarded as maximal ones requiring further refining and justification. It is necessary to ~~delve~~ investigate more deeply into the conditions of the quasistationarity of the processes of the flow around particles, the interaction between particles at low velocities of ambient flow and at small mutual distances, and to compare the effect of hydrodynamic forces with the effect of orthokinetic coagulation. Most likely, the course of the over-all process is determined by the conjoint action of [redacted] both these factors.

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